

Scaling-up an integrated electrodisinfection- electrocoagulation process

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Abstract

This work focuses on the scaling-up of an integrated electrodisinfection-
electrocoagulation (ED-EC) process, especially suited for the reclamation of actual urban
treated wastewater, equipped with Boron Doped Diamond (BDD) anodes and iron bipolar
electrodes. The system operates in continuous mode and in the prototype the anode area
was increased three times (anodic oxidation) and the bipolar electrode area fifteen times
(electrocoagulation) with respect to the system used at bench scale. Results show that it
is possible to attain the complete and simultaneous disinfection and turbidity removal by
applying current densities within the range 5-10 A m⁻². Free and combined chlorine
species were electrogenerated from the chloride contained in the effluents (no reagents
were added) being these species responsible for the removal of microorganisms.
Likewise, iron coagulant species coming from the electro-dissolution of the anodic side
of bipolar electrodes promote turbidity removal. In the scaled-up prototype, it was

25 achieved a more efficient turbidity removal, because of the increase of the bipolar
26 electrode area. Finally, it was proved that for electric charges below 0.07 kAh m^{-3} the
27 reclamation of urban treated wastewater could be reached, avoiding the formation of
28 hazardous chlorates and perchlorates even at current densities higher than 7 A m^{-2} .

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30 **Keywords:** electrolysis, *E. coli*, electrocoagulation, turbidity, scale-up.

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39 **Highlights**

- 40 - Complete disinfection and turbidity removal with ED-EC process at pilot scale.
- 41 - Free and combined chlorine species are the main responsible of the disinfection.
- 42 - Electric charges of 0.07 kAh m^{-3} avoid the formation of hazardous DBPs.
- 43 - Higher production of coagulant species using 5 bipolar electrodes per stack.
- 44 - Lower energy consumption at 7 A m^{-2} passing electric charges of 0.07 kAh m^{-3} .

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50 **1. Introduction**

51 In the recent years, urban treated wastewater reclamation has claimed great interest due
52 to the very important water scarcity in different regions of the World (Bixio *et al.* 2005;
53 Hochstrat *et al.* 2005; Lu *et al.* 2013; Baresel *et al.* 2015; Arden & Ma 2018). This
54 situation is acuter in countries where it is difficult to guarantee the drinking water supply.
55 For this reason, wastewater reclamation could become an alternative water resource. In
56 this context, different technologies are being developing nowadays to treat urban
57 wastewater (Gómez *et al.* 2006; Ferro *et al.* 2015; Fiorentino *et al.* 2016; Gutiérrez-Alfaro
58 *et al.* 2018). They are designed by considering that for a safe use of this water, pathogens
59 should be removed and two parameters are considered to be the main targets: the fecal
60 pathogen *Escherichia coli* (*E. coli*) and the turbidity.

61 Physico-chemical processes have been widely studied for the treatment of this type of
62 wastewater. However, the important increase produced in the conductivity of the treated
63 waste becomes a very important drawback and promotes electrocoagulation as a potential
64 alternative (Cañizares *et al.* 2009b; Zaleschi *et al.* 2012; Zaleschi *et al.* 2013). The
65 electrochemically-assisted coagulation consists of the in-situ production of coagulant
66 agents from the electro-dissolution of a sacrificial aluminum or iron anodes (Pouet &
67 Grasmick 1995). The main different of this electrochemical technology with respect to
68 conventional coagulation is that in electrocoagulation the reagent added is the metal
69 hydroxide directly and not a salt of a multivalent cation (such as FeCl_3 or $\text{Al}_2(\text{SO}_4)_3$) that
70 has to be later neutralized. Therefore, electrochemical technologies may be considered
71 cleaner and more environmentally friendly.

72 In addition to electrocoagulation, other electrochemically-based technologies, the
73 Electrochemical Advanced Oxidation Processes (EAOPs), have also been proposed

74 wastewater reclamation (Sirés *et al.* 2014). These technologies are based on the
75 production of oxidants with high disinfection capacity. One of them is the Conductive-
76 Diamond Electrochemical Oxidation (CDEO) (Cano *et al.* 2011; Cano *et al.* 2012; Cano
77 *et al.* 2016), which consists of the production of disinfectant species from the
78 electrooxidation of the ions naturally contained in wastewater using anodic oxidation with
79 diamond electrodes. Previous works demonstrated that it is possible to attain the complete
80 disinfection of the effluents without the addition of chemicals. In addition, it has been
81 demonstrated that electrocoagulation and CDEO can be combined efficiently, leading to
82 a technology (so-called electrodisinfection-electrocoagulation, ED-EC) capable to
83 simultaneously decrease the concentration of *E. coli* contained in actual urban treated
84 wastewater and a decrease in turbidity (Cotillas *et al.* 2013; Llanos *et al.* 2014).

85 At this point, it is important to take in mind that most of technologies for wastewater
86 reclamation has been checked at bench scale and, hence, it is necessary to study the scale-
87 up of these processes to ensure a proper operation with high volume of wastewater. In
88 this context, we previously reported the disinfection of urban treated wastewater by
89 electrolysis and photo-electrolysis with diamond anodes at pilot scale, finding an efficient
90 removal of *E. coli* at soft operating conditions (Cano *et al.* 2016; MartÃ-n de Vidales *et*
91 *al.* 2016). With this background, this work focuses on the scale-up of an integrated ED-
92 EC process with diamond anodes and iron bipolar electrodes for the reclamation of urban
93 treated wastewater. The scaled-up pilot process operates in continuous mode and with
94 respect to the bench scale setup it has underwent a three-times increase in the area of the
95 anode (anodic oxidation) and fifteen times in the bipolar sacrificial electrode area
96 (electrocoagulation). The influences of the current density (within the range 5-10 A m⁻²)
97 and the electric charge passed (within the range 0.01-0.1 kWh m⁻³) on the kinetic process
98 and the process efficiency has been studied.

100 **2. Material and methods.**

101 **2.1. Analytical techniques.**

102 Most probable number (MPN) technique was used for the estimation of *E. coli*
103 concentration (APHA-AWWA-WPCF 1998). Microorganism counts were carried out by
104 the multiple tube fermentation during 24 h at 44°C. Five tubes were used for each dilution
105 (1:10, 1:100, 1:1000). The presence of *E. coli* was considered positive in tubes with
106 yellow color whereas red tubes (initial color of media culture) were considered as
107 negative. The composition of media culture has been previously reported elsewhere
108 (Cotillas *et al.* 2015).

109 Turbidity was measured using a 115 Velp Scientifica turbidimeter following the standard
110 method reported in literature.

111 The concentration of ions was measured by ion chromatography. The chromatography
112 system was a Shimadzu LC-20A coupled to a conductivity detector. The column Shodex
113 IC I-524A was used to determine the anions. Furthermore, a column Shodex IC YK-421
114 was used to analyze the cations. The mobile phase consisted of 2.5 mM phthalic acid at
115 pH 4.0 for the determination of anions with a flow rate of 1 mLmin⁻¹. A solution of 5 mM
116 tartaric acid, 1 mM dipicolinic acid and 24.3 mM boric acid was used as mobile phase for
117 the determination of cations with a flow rate of 1 mL min⁻¹.

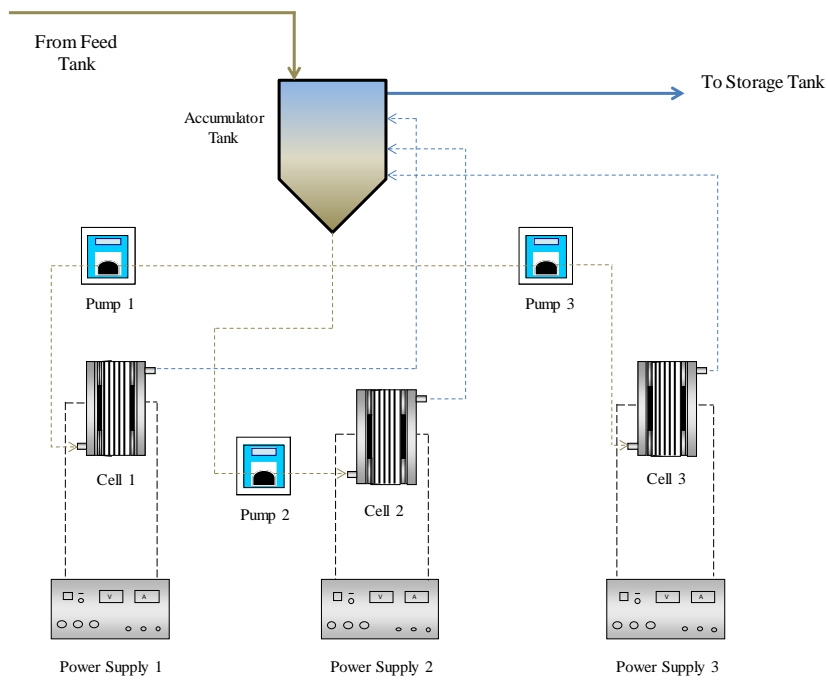
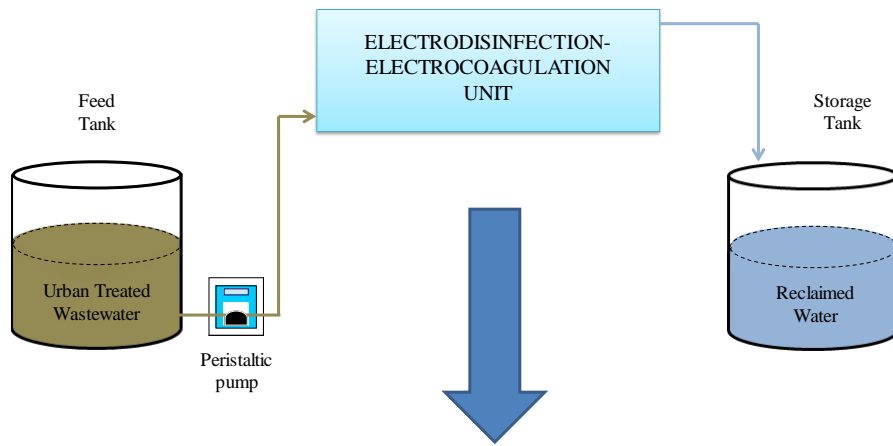
118 Hypochlorite was analyzed by titration with 0.001 M As₂O₃ in 2 M NaOH (Wilpert 1957;
119 Freytag 1959) because of the peak of this anion interferes with that of chloride in ion
120 chromatography system. Inorganic chloramines were measured by DPD standard method
121 described in literature (APHA-AWWA-WPCF 1998).

122 Metal concentration (Fe) was measured by inductively coupled plasma spectrometer
123 (Liberty Sequential, Varian) according to a standard method (plasma emission
124 spectroscopy) (APHA-AWWA-WPCF 1998). Samples were diluted to 50:50 (v/v) using
125 HNO₃ to ensure total solubility of the metal.

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127 **2.2. Experimental setup.**

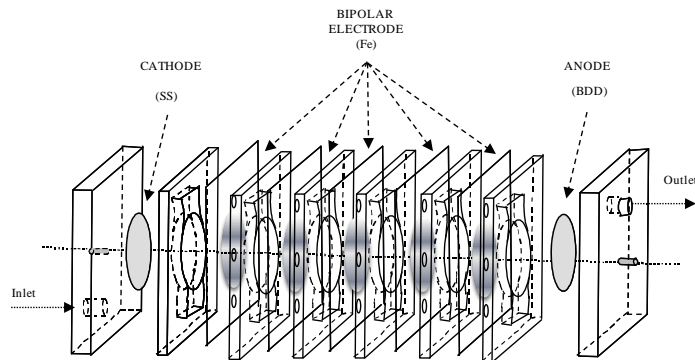
128 The integrated electrodisinfection-electrocoagulation process was carried out in a pilot
129 plant composed of three electrochemical cells (Figure 1). Each cell was a filter press type
130 equipped with a BDD anode, a stainless-steel (SS) cathode and five perforated iron
131 bipolar electrodes placed between anode and cathode (Figure 2). With this system the
132 anodic area was increased three times and the bipolar electrode area was increased fifteen
133 times with respect to the setup used at bench scale (Llanos *et al.* 2014). BDD and SS were
134 circular with a geometric area of 78.5 cm². The electrode gap between anode and cathode
135 was 40 mm and between bipolar electrodes was 5 mm. The sp³/sp² ratio of diamonds used
136 was within the range 211-287 and the thickness was between 2.71-2.89 μm. Three power
137 supplies (Delta Electronika ES030-10, 0-30 V, 0-10 A) were used to apply the current in
138 the ED-EC experiments. The system works in continuous mode with a peristaltic pump
139 (JP selecta Percom N-M328) which continuously provides fresh urban treated
140 wastewater. Reclaimed water was stored into a tank.



141

142 **Figure 1.** Electrodisinfection-electrocoagulation pilot plant for wastewater reclamation.

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144

145 **Figure 2.** Detail of the electrochemical cell (stack) used in pilot plant.

146 **2.3. Experimental procedure.**

147 Urban treated wastewater was directly collected at the secondary clarifier of the WWTP
148 of Ciudad Real (80,000 inhabitants). The influent of this plant comes from domestic
149 activities and its composition is very uniform. The average microbiological and physical-
150 chemical composition characteristics of the samples are shown in Table 1. Experiments
151 were carried out under galvanostatic conditions and continuous mode (typical operation
152 mode in industrial plants). First, fresh wastewater is fed to the accumulator tank from
153 which is boosted to the electrochemical cells by means of peristaltic pumps. Next, the
154 effluent is recirculated to the accumulator tank with a similar flow rate than that used for
155 the experiments at bench scale ($50 \text{ dm}^3 \text{ h}^{-1}$) to maintain the same hydrodynamics inside
156 the cells (Llanos *et al.* 2014). Finally, reclaimed water is obtained by overflow from the
157 accumulator tank.

158 **Table 1.** Average composition of wastewater.

| Parameter | Value |
|---|-------------|
| Chloride (mg dm^{-3}) | 82.19 |
| Nitrate (mg dm^{-3}) | 14.80 |
| Sulfate (mg dm^{-3}) | 152.10 |
| Ammonium (mg dm^{-3}) | 18.89 |
| Iron (mg dm^{-3}) | n.d.* |
| Turbidity (NTU) | 6-8 |
| <i>E. coli</i> (CFU 100 ml^{-1}) | 1,100-2,200 |

159 *n.d.- non detectable

160 Microorganisms concentration and disinfectant compounds (free and combined chlorine
161 species) were measured immediately. Hence, it was not required the addition of chemicals
162 (e.g. $\text{Na}_2\text{S}_2\text{O}_3$) to stop the reaction between disinfectants and microorganisms. The current

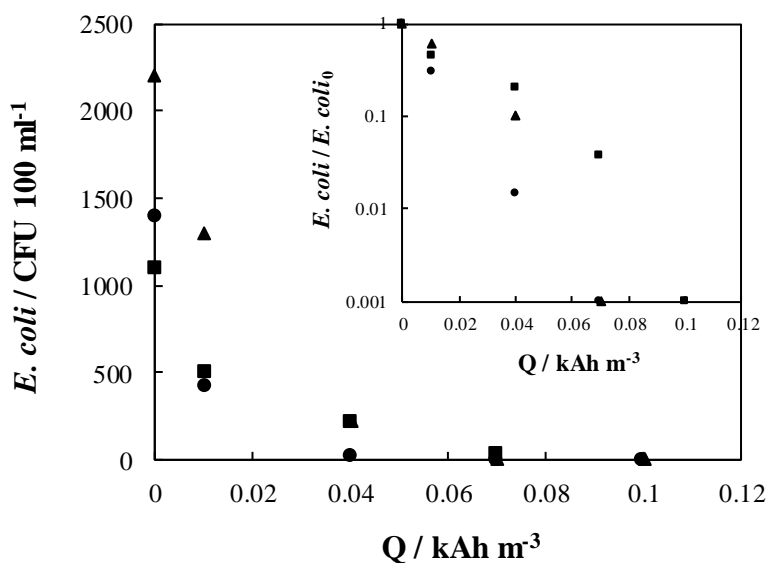
163 density and the applied electric charge were fixed by taking into account previous results
 164 obtained at bench scale (Llanos *et al.* 2014). In continuous mode, the applied electric
 165 charge was calculated following the Equation 1 where Q is the applied electric charge
 166 (kAh m^{-3}), I is the current intensity (kA) and q is treatment capacity of the plant ($\text{m}^3 \text{h}^{-1}$).

$$167 \quad Q = I / q \quad [1]$$

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169 3. Results and discussion.

170 Figure 3 shows the changes underwent by the concentration of *E. coli* with the applied
 171 electric charge during the ED-EC at different current densities.

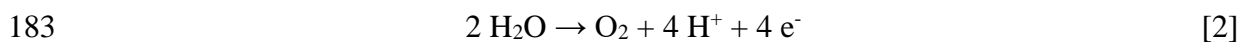


172

173 **Figure 3.** Influence of the current density on the removal of *E. coli* during the ED-EC at
 174 pilot scale. Anode: BDD; cathode: SS; bipolar electrode: Fe; (■) j: 5 A m⁻²; (▲) j: 7 A m⁻²;
 175 (●) j: 10 A m⁻².

176 As can be observed, the concentration of *E. coli* decreases with the applied electric charge,
 177 reaching a total removal of microorganisms (complete disinfection) for all the current
 178 densities studied. However, the process efficiency is clearly influenced by this parameter:

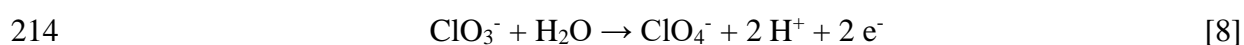
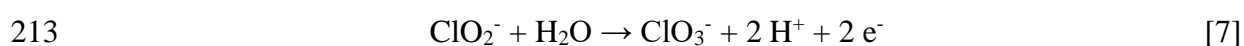
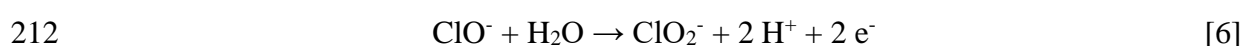
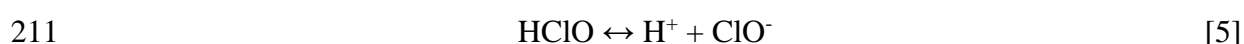
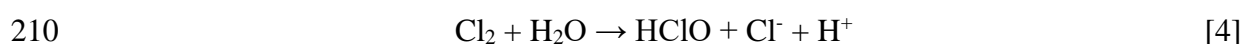
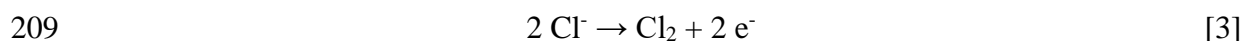
179 the higher current densities, the higher disinfection efficiency. This is an unexpected
180 behavior during the electrolysis of wastewater because higher current densities are
181 expected to promote the formation of side reactions such as oxygen evolution (Eq. 2),
182 decreasing the process efficiency (Panizza & Cerisola 2009).



184 In comparing these results with those obtained in the EC-ED process at the bench-scale,
185 it is important to highlight that the applied electric charge required to attain a complete
186 disinfection of the effluent at pilot scale is higher than that needed at bench scale.
187 Specifically, charges lower than 0.01 kAh dm⁻³ lead to a complete depletion of *E. coli* at
188 bench scale (Llanos *et al.* 2014) whereas values higher than 0.06 kAh dm⁻³ are required
189 when working at pilot scale. The difference observed can be related to the operating mode
190 in both scales: discontinuous (bench scale) and continuous (pilot scale). At pilot scale,
191 the effluent passes only once through the electrochemical system, whereas this effluent is
192 continuously recirculated to the electrochemical cell during the process at bench scale.
193 This increases the contact time of microorganisms with the electrode, decreasing the
194 charge required for their disinfection.

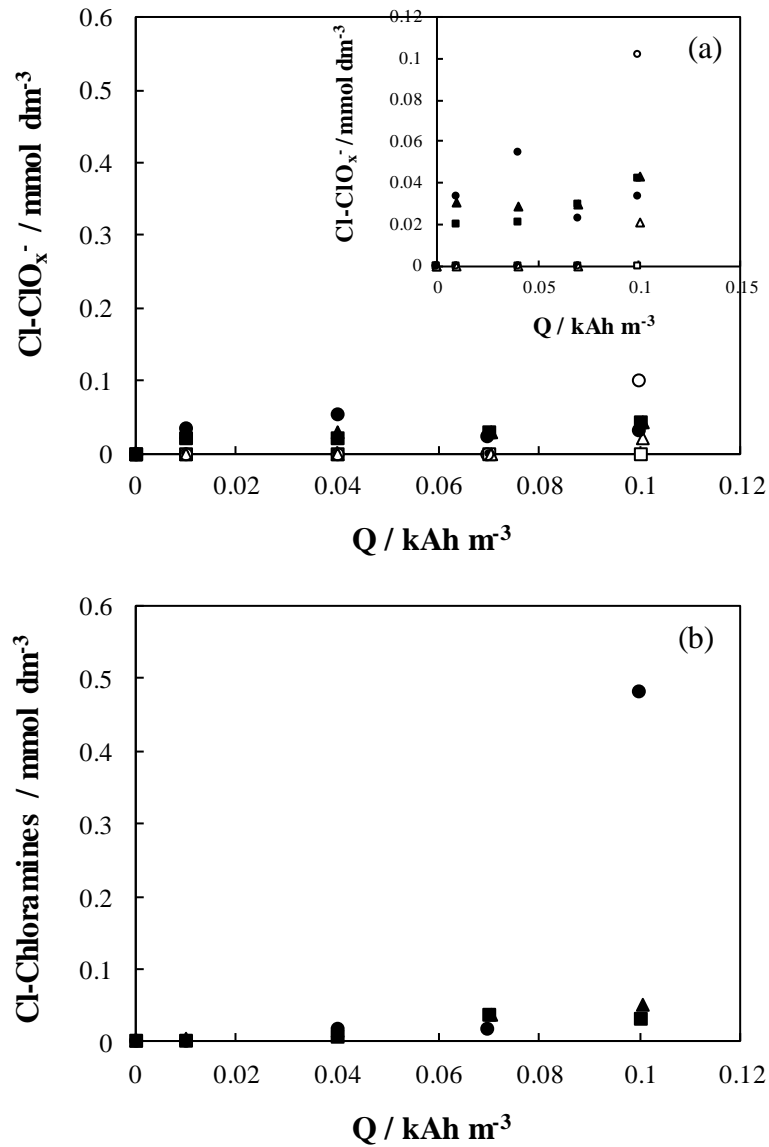
195 The removal of microorganisms can be carried out by different mechanisms during the
196 electrochemical treatment: direct or indirect disinfection. In previous works, we
197 demonstrated that the electrodisinfection with diamond anodes takes mainly place by the
198 action of electrogenerated disinfectant species from the ions naturally contained in
199 wastewater (indirect disinfection) (Cano *et al.* 2012; Cotillas *et al.* 2018). Specifically,
200 chlorides are electrooxidized to chlorine and hypochlorite during the process (Eqs. 3-5).
201 These species present a high disinfectant capacity which significantly contribute to the
202 removal of microorganisms. Likewise, hypochlorite can be electrochemically oxidized to
203 other chlorine compounds in high oxidation state such as chlorate and perchlorate (Eqs.

204 6-8) (Bergmann & Rollin 2007; Bergmann 2010). However, they are harmful to human
 205 health and, hence, their presence should be avoided in wastewater. To shed light about
 206 the real contribution of chlorine compounds to the disinfection of urban treated
 207 wastewater at pilot scale, Figure 4a shows the concentration of these species with the
 208 applied electric charge at different current densities.



215 Hypochlorite concentration increases with the applied electric charge for all the tests
 216 carried out. However, different behaviors can be seen depending on the current density
 217 applied. At 5 A m^{-2} , the concentration of this species is lower than that obtained during
 218 the treatment at values higher than 7 A m^{-2} . This also explains the lower disinfection
 219 efficiency observed under these conditions (Figure 3). A similar trend can be seen when
 220 working at 7 A m^{-2} but, in this case, the maximum electrogenerated concentration was
 221 higher at low applied electric charges (0.03 vs. $0.02 \text{ mmol Cl dm}^{-3}$). Finally, at 10 A m^{-2} ,
 222 there is an initial increase followed by a decrease in hypochlorite profile. Under these
 223 conditions, the maximum concentration of this species was higher than $0.05 \text{ mmol Cl dm}^{-3}$.
 224 ³. On the other hand, the decrease observed can be related to the promotion of
 225 hypochlorite to other chlorine compounds such as chlorate. In this context, the
 226 concentration of this species increases during the treatment from current densities of 7 A
 227 m^{-2} and electric charges higher than 0.07 kAh m^{-3} . At this point, it is important to remark

228 that the charge required to attain a complete disinfection at current densities higher than
 229 7 A m^{-2} was 0.07 kAh m^{-3} and, under these operating conditions, no chlorine compounds
 230 in high oxidation state were electrogenerated. Therefore, it is possible to attain a complete
 231 disinfection of urban treated wastewater by an integrated ED-EC process at pilot scale,
 232 avoiding the formation of chlorates.

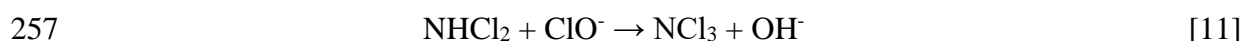
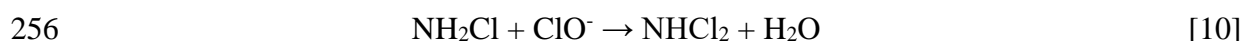
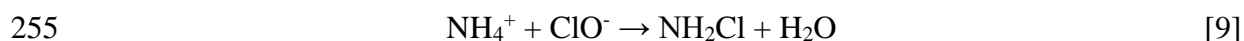


233
 234 **Figure 4.** Chlorine speciation as function of the applied electric charge during the ED-
 235 EC at pilot scale. Anode: BDD; cathode: SS; bipolar electrode: Fe; (■) j : 5 A m^{-2} ; (▲) j :

236 7 A m⁻²; (●) j: 10 A m⁻². (a) Free chlorine; black symbols: ClO⁻; white symbols: ClO₃⁻.
237 (b) Combined chlorine.

238 The concentration of free chlorine compounds during the ED-EC process at pilot scale is
239 lower than that reported in literature when working at bench scale (Llanos *et al.* 2014).
240 This can be related to a different initial concentration of chlorides in actual wastewater.
241 Specifically, the average chloride concentration was around 80 mg dm⁻³ during the
242 experiments at pilot scale whereas values higher than 200 mg dm⁻³ were found at bench
243 scale. Hence, there are more available chlorides to be oxidized during the treatment at
244 bench scale, favoring the production of large amounts of disinfectant species in
245 wastewater and the subsequent removal of microorganisms at lower applied electric
246 charges.

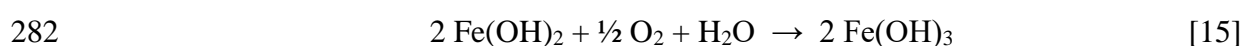
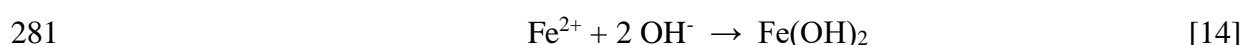
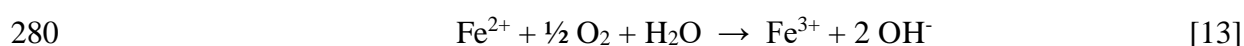
247 Actual effluents present different ions in their composition such as sulfate, sodium or
248 ammonium (Cotillas *et al.* 2016). This last one is very important from the point of view
249 of disinfection processes since it can react with free chlorine present in wastewater,
250 favoring the formation of combined chlorine compounds, commonly called chloramines
251 (Eqs. 9-11) (Gray 2013; Huang *et al.* 2016). These species present an excellent
252 disinfectant capacity, but they are less aggressive than hypochlorite. For this reason, the
253 concentration of chloramines was also monitored during the ED-EC process at pilot scale.
254 Figure 4b shows the evolution of chloramines at different current densities.

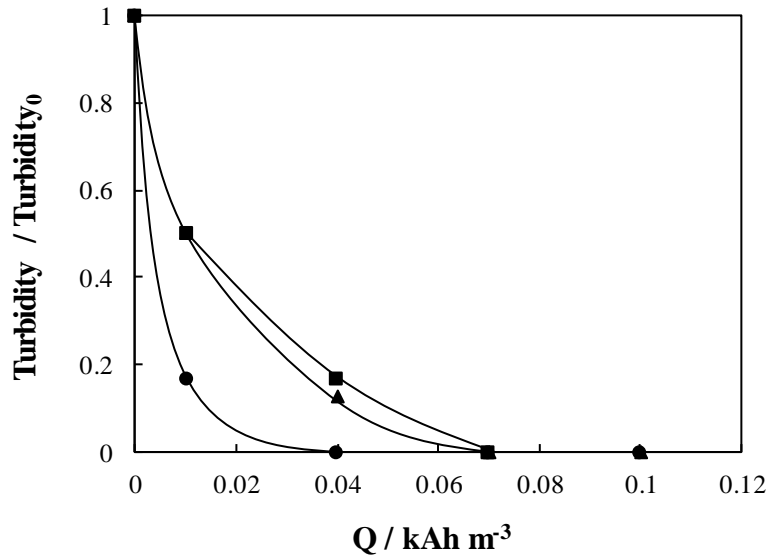
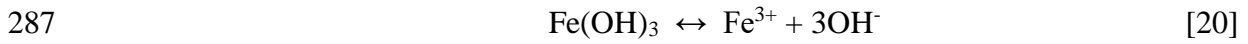
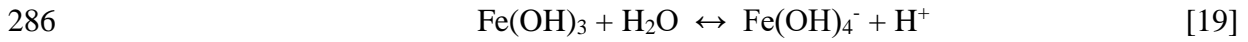
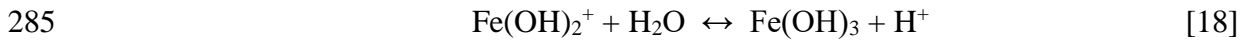
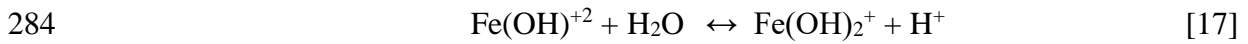


258 As can be observed, the concentration of chloramines increases during the treatment,
259 regardless the applied current density. The presence of these species reveals that the

260 removal of microorganisms takes also place by the combined effect of both hypochlorite
 261 and chloramines during the ED-EC process at pilot scale. The use of current densities of
 262 10 A m^{-2} leads to a higher production of chloramines because of the higher concentration
 263 of electrogenerated hypochlorite (Figure 4a). At current densities lower than 7 A m^{-2} , the
 264 final concentration of chloramines is similar than that obtained for free chlorine (< 0.01
 265 mmol Cl dm^{-3}). This suggests that chlorine species are quickly reacted during ED-EC at
 266 pilot scale. It is important to take in mind that free and combined chlorine compounds are
 267 continuously reacting in the system and, hence, it is only possible to measure the
 268 concentration which has not reacted yet.

269 On the other hand, the use of iron bipolar electrodes in the electrochemical cells without
 270 direct connection to the power supply (wireless connection) promotes the formation of
 271 soluble and insoluble iron coagulant species in wastewater by the electrodisolution of
 272 the anodic side of bipolar electrodes (Eqs. 12-20) (Garcia-Segura *et al.* 2017). These
 273 species are the main responsible of turbidity removal in wastewater (Sadeddin *et al.*
 274 2011). The occurrence of one or another species will depend on the metal concentration
 275 and the pH of the solution (Gregory & Duan 2001; Duan & Gregory 2003; Cañizares *et*
 276 *al.* 2006; Cañizares *et al.* 2009a). Figure 5 shows the evolution of turbidity with the
 277 applied electric charge during the ED-EC process at pilot scale and different current
 278 densities.





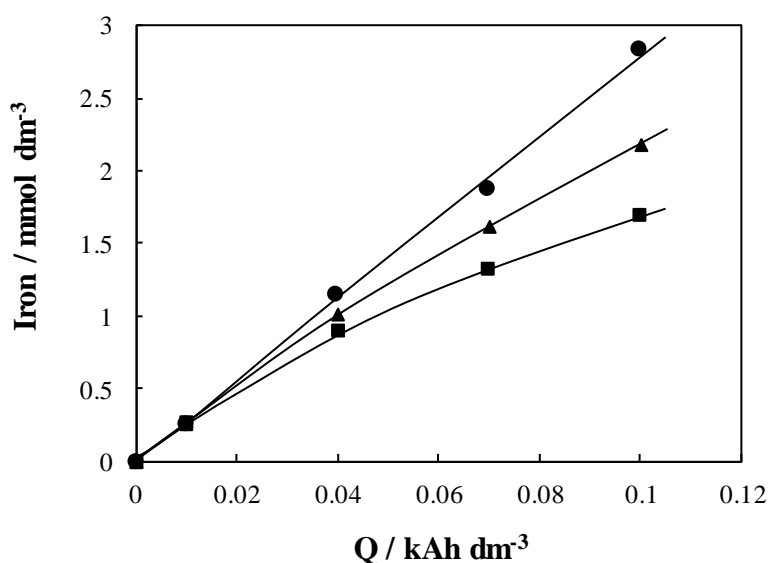
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289 **Figure 5.** Influence of the current density on turbidity removal during the ED-EC at pilot
 290 scale. Anode: BDD; cathode: SS; bipolar electrode: Fe; (■) j: 5 A m⁻²; turbidity₀: 6 NTU;
 291 (▲) j: 7 A m⁻²; turbidity₀: 8 NTU; (●) j: 10 A m⁻²; turbidity₀: 6 NTU.

292 Turbidity decreases with the applied electric charge for all the tests carried out.
 293 Specifically, it is possible to attain a complete turbidity removal applying electric charges
 294 lower than 0.07 kAh m⁻³, regardless the current density applied. This fact reveals that the
 295 use of five iron bipolar electrodes per cell is enough to completely decrease this parameter
 296 in wastewater. At bench scale, it was necessary to apply current densities higher than 9 A
 297 m⁻² and charges near to 0.05 kAh m⁻³ to attain a complete turbidity removal, because only
 298 one iron bipolar electrode was used per cell (Llanos *et al.* 2014). However, under these
 299 conditions, chlorine compounds in high oxidation state were generated, limiting the
 300 applicability of the technology. Hence, it is possible to attain not only a complete

301 disinfection but also a complete turbidity removal with the system proposed at pilot scale
302 without disinfection-by-products.

303 Furthermore, it should be noted that turbidity is completely removed at electric charges
304 of 0.04 kAh m^{-3} when working at higher current densities (10 A m^{-2}). This value is lower
305 than that obtained for current densities lower than 7 A m^{-2} and it can be related to the
306 concentration of coagulant species in the system. To check this, metal concentration was
307 also monitored during the process at pilot scale. Results are shown in Figure 6.



308

309 **Figure 6.** Iron electrodisolved during the ED-EC at pilot scale. Anode: BDD; cathode:
310 SS; bipolar electrode: Fe; (■) $j: 5 \text{ A m}^{-2}$; (▲) $j: 7 \text{ A m}^{-2}$; (●) $j: 10 \text{ A m}^{-2}$.

311 As can be observed, iron concentration linearly increases with the applied electric charge.

312 As expected, the maximum concentration of metal was reached at 10 A m^{-2} , which is

313 directly related to the more efficient turbidity removal observed under these conditions

314 (Figure 5). The nature of iron coagulant species indicates the main mechanism for

315 turbidity removal by coagulation which depends on the pH. In this context, the pH of

316 wastewater remained constant between 7 and 8 during the process without the addition of

317 chemicals. According to literature (Cañizares *et al.* 2009a), this indicates that the

318 dominant species in the system are insoluble hydroxide precipitates, being the main
319 mechanism for turbidity removal the sweep flocculation.

320 Finally, once the ED-EC process at pilot scale has been successfully tested for the
321 reclamation of urban treated wastewater, the energy consumption per unit volume has
322 been calculated, according to equation 21:

$$323 \quad W \text{ (kWh m}^{-3}\text{)} = Q \times V \quad [21]$$

324 Where Q is the electric charge passes in kAh m⁻³ and V is the applied voltage in V. This
325 parameter has been calculated taking into account the total reclamation of urban treated
326 wastewater: total disinfection and turbidity removal. Table 2 shows the energy
327 consumption at different current densities.

328 **Table 2.** Energy consumption.

| j (A m⁻²) | Q (kAh m⁻³) for total wastewater reclamation | W (kWh m⁻³) |
|-----------------------------|--|-------------------------------|
| 5 | 0.1 | 2.41 |
| 7 | 0.07 | 2.24 |
| 10 | 0.07 | 3.04 |

329
330 Results show a higher energy consumption for the treatment carried out at 10 A m⁻². This
331 is an expected value taking into account that it is the higher current density applied.
332 However, the lower energy consumption was registered for the test carried out at 7 A m⁻²
333 not for the lower current density applied. This fact is due to the higher electric charge
334 required to attain a complete reclamation of wastewater when working at 5 A m⁻² (0.1 vs.
335 0.07 kAh m⁻³). For this reason, the proper conditions to carried out the treatment of urban
336 wastewater for reclamation purposes by an integrated ED-EC process at pilot scale are
337 current densities of 7 A m⁻² and electric charges until 0.07 kAh m⁻³. Under these

338 conditions, the energy consumption is lower and, as mentioned above, the production of
339 hazardous compounds is avoided.

340

341 **4. Conclusions.**

342 From this work, the following conclusions can be drawn:

343 - Urban treated wastewater can be completely reclaimed by an integrated
344 electrodisinfection-electrocoagulation process at pilot scale using diamond
345 anodes and iron bipolar electrodes. The process efficiency is slightly lower at pilot
346 scale due to the continuous operation mode which leads to a lower production of
347 disinfectant species in the effluent.

348 - The use of current densities within the range $5-10 \text{ A m}^{-2}$ and applied electric
349 charges until 0.1 kAh dm^{-3} leads to a complete disinfection and turbidity removal.
350 In-situ electrogenerated free and combined chlorine species are the main
351 responsible for disinfection whereas iron coagulant species electro-dissolved lead
352 to an efficient turbidity removal.

353 - Chlorine compounds in high oxidation are generated during the ED-EC process
354 at pilot scale. Hence, it is recommendable to limit the applied electric charge to
355 0.07 kAh m^{-3} when working at current densities higher than 7 A m^{-2} . Under these
356 conditions, it is possible to achieve the complete reclamation of urban treated
357 wastewater, avoiding the formation of toxic compounds. Likewise, the energy
358 consumption calculated for these conditions was the lowest.

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365

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